

Primordial Deuterium and Big Bang Nucleosynthesis: A Tale of Two Abundances

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Abstract. Recent confrontations of the predictions of standard big bang nucleosynthesis (SBBN) with the primordial abundances of the light nuclides inferred from observational data reveal a conflict. Simply put, compared to theoretical expectations the inferred primordial abundances of either deuterium or helium-4 (or both) are “too small”. Here I outline the “tension” between D and ^4He in the context of SBBN. The incipient crisis for SBBN may be resolved by observations of deuterium in nearly pristine environments such as the high-redshift, low-metallicity QSO absorbers. At present the big bang abundances of deuterium inferred from such data fall into two, apparently mutually exclusive, groups. I describe the deuterium dichotomy and its implications for SBBN as well as for cosmology in general.

1. Introduction

The Universe is observed to be expanding and is filled with radiation (CBR at 2.7K) and ordinary matter (baryons). In the past, when the density and temperature (thermal energy) were much higher, conditions may have permitted the synthesis of complex nuclei starting from neutrons and protons as the basic building blocks. Which nuclei are synthesized and in what relative abundances depends on the details of the competition among the radiation density, the matter density and the early expansion rate. In the context of the simplest, “standard”, hot big bang cosmology only the lightest nuclides (D, ^3He , ^4He and ^7Li) are produced with astrophysically interesting yields. Furthermore, in SBBN these yields depend on only one “free” parameter, the ratio of the nucleon (baryon) density to the photon density (today): $\eta \equiv n_{\text{B}}/n_{\gamma}$; $\eta_{10} \equiv 10^{10}\eta$. In Figure 1 the predicted SBBN yields (for D, ^3He and ^7Li relative to hydrogen by number and for Y_{P} , the ^4He mass fraction) are shown as functions of η . Clearly SBBN is - in principle - an overdetermined theory, predicting four primordial abundances at the expense of one parameter. If the primordial abundance could be determined for only one of the light nuclides η would be fixed and SBBN would predict the abundances of the other three. Confrontation between such predictions and the observational data constitutes a test of the standard model. In practice this approach has encountered many obstacles.

For example, until recently deuterium has been observed “here and now” in the local interstellar medium (ISM) or in the solar system. The good news is

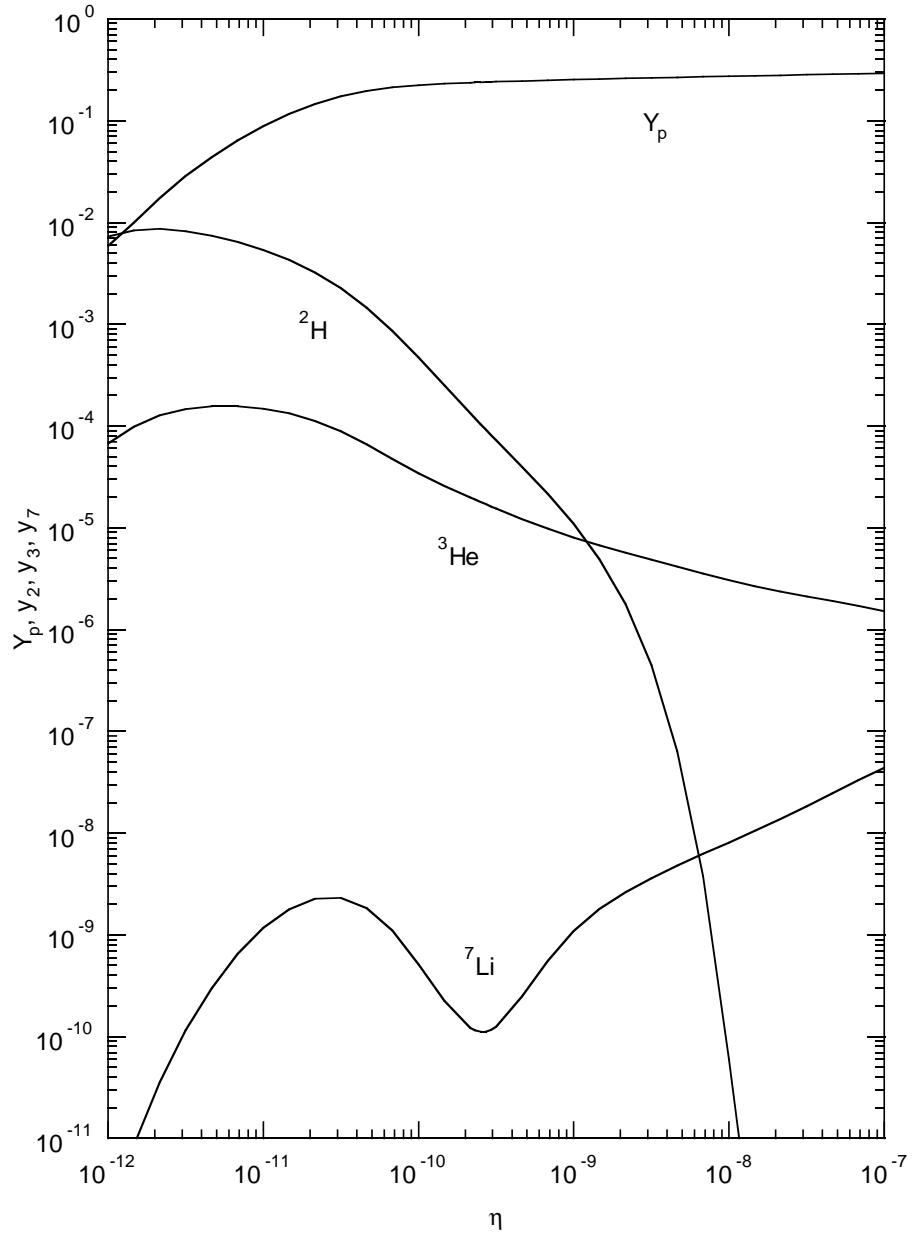


Figure 1. SBBN-predicted abundances of ^4He (mass fraction Y_p), D ($y_{2P} = (\text{D}/\text{H})_P$), ^3He ($y_{3P} = (^3\text{He}/\text{H})_P$) and ^7Li ($y_{7P} = (^7\text{Li}/\text{H})_P$) as functions of η , the present ratio of nucleons to photons. This graph has been provided by D. Thomas.

that the evolution of D from the big bang (“there and then”) is straightforward: In the course of Galactic evolution D is destroyed (burned to ^3He and beyond) whenever gas is incorporated into stars. Thus the abundance (mass fraction X_2) of deuterium has only decreased since the big bang ($X_{2P} \geq X_2$). The bad news is that, in the absence of reliable constraints on the amount of chemical evolution (up to the present or to the time the solar nebula formed), we don’t know by how much. Conventional models of chemical evolution, constrained by the size and distribution (in space as well as in time) of various heavy-element abundances, predict only modest D-destruction by a factor of 2 – 3 or so (e.g., Audouze & Tinsley 1974; Vangioni-Flam & Audouze 1988; Tosi 1988a,b, 1996; Steigman & Tosi 1992, 1995; Fields 1996). If so, current data point towards a “low” primordial abundance implying a “high” η (see Fig. 1). However, unconventional models have been designed (e.g., Scully et al. 1996) which arrange for much more D-destruction while maintaining consistency with the other observational data. If this, or something like it, is the path chosen by the Galaxy the primordial abundance of D might be much larger than current data suggest, permitting a smaller nucleon abundance (see Fig. 1).

The extraction of the primordial abundance of ^3He from solar-system and/or ISM (H II regions) data (Bania, Rood & Wilson 1987; Rood, Bania & Wilson 1992; Balser et al. 1994) is even more problematic (e.g., Dearborn, Steigman & Tosi 1996) given that some ^3He is destroyed, some survives, and new ^3He is produced in the course of the evolution of stars of different masses. The delicate balance between stellar and Galactic evolution renders challenging in the extreme an accurate inference of the primordial abundance. However, some qualitative features have emerged from such attempts. By the time stars reach the main sequence they have already converted any prestellar deuterium to helium-3; the more D destroyed, the more ^3He has passed through stars. Since not all the pre-main sequence helium-3 ($\text{D} + ^3\text{He}$) is destroyed (by stars of any mass), there is some correlation between the observed abundances of D and ^3He and their primordial values (e.g., Yang et al. 1984; Walker et al. 1991; Steigman & Tosi 1992, 1995). Consequently, in most analyses of SBBN it is not ^3He but some combination of D and ^3He which provides a means of testing for consistency.

Although not without problems of its own, in some ways lithium is simpler. Since the pioneering work of the Spites (Spite & Spite 1982a,b; Spite, Maillard & Spite 1984; Spite & Spite 1986) a large body of observations of lithium in very old, very metal-poor Pop II halo stars has been accumulated (Rebolo, Molaro & Beckman 1988; Hobbs & Pilachowski 1988; Thorburn 1994; Molaro, Primas & Bonifacio 1995; Spite et al. 1996). The very low metallicity guarantees that the extrapolation to primordial is minimal. But the very great ages of these stars open the possibility that they may have altered their surface abundance of ^7Li from its prestellar value (e.g., Chaboyer et al. 1992; Pinsonneault, Deliyannis & Demarque 1992; Charbonnel & Vauclair 1992, 1995). Further, since the large number of careful, independent observations ensures high statistical accuracy, it is uncertainties in the model atmospheres and the temperature scale for these metal-poor stars which dominate the abundance errors. Nevertheless, few would disagree that the data point towards a low primordial abundance, considerably below the Pop I value (see, e.g., Steigman 1996), near the minimum of the “lithium valley” (see Fig. 1). At present, uncertainties in the precise value of the “Spite plateau” and in the amount of possible stellar dilution/destruction

relegate ${}^7\text{Li}$ to the role of offering an approximate rather than a precise test of SBBN (see, however, Fields & Olive 1996; Fields et al. 1996): The inferred primordial lithium abundance is consistent with a range in nucleon abundance from “low” to “high” values of η (see Fig. 1).

Helium-4 provides the last, best hope for testing SBBN quantitatively. As the second most abundant element (after hydrogen), ${}^4\text{He}$ may be observed throughout the Universe (not just “here and now”). And large numbers of careful observations may be used to determine its abundance to high statistical accuracy. High-quality data for individual observations achieve 5% accuracy (≈ 0.012 in Y) and there now exist several dozen such determinations. However, the flip side of the ${}^4\text{He}$ coin is that the predicted primordial abundance (mass fraction, Y_P) is a very weak function of the one free SBBN parameter (η) as is evident from Figure 1. Thus, to provide a key test of the consistency of SBBN, it is necessary to pin down Y_P very accurately. Since stars do produce new ${}^4\text{He}$ along with the heavy elements (“metals”), the correction for evolution must be minimized or understood very well. For this reason most effort in the search for the holy grail (Y_P) has been channelled towards observations of the low-metallicity, extragalactic H II regions (Searle & Sargent 1971; Peimbert & Torres-Peimbert 1974; Lequeux et al. 1979; Kunth & Sargent 1983; Torres-Peimbert, Peimbert & Fierro 1989; Pagel et al. 1992; Skillman & Kennicutt 1993; Skillman et al. 1994; Izotov, Thuan & Lipovetsky 1994). It is in the interpretation of this body of data that unknown (or unquantified) systematic errors may rear their ugly heads (Davidson & Kinman 1985; Pagel et al. 1992; Sasselov & Goldwirth 1995; Peimbert 1996; Skillman 1996). Current data (see Olive & Steigman 1995, 1996 and references therein) point towards a “low” value of Y_P , indicating a “low” value of η (see Fig. 1). But an unaccounted-for systematic offset in the primordial mass fraction, ΔY_{sys} , might raise Y_P , and correspondingly, the upper bound to η .

2. The Tension Between Deuterium and Helium-4

Until recently the confrontation of the SBBN predictions with the primordial abundances inferred from increasingly extensive and accurate observational data has been a spectacular success, confirming the consistency of SBBN, zeroing in on the universal abundance of nucleons (η) and constraining non-standard models of particle physics (see, e.g., Walker et al. 1991 and references therein). However, it has begun to be increasingly clear that the very tight constraints inferred from this confrontation of theory with observations are a precursor to the conclusion that the “standard” model is not providing a very good fit to the data. One way to describe this emerging crisis for SBBN is through the parameter N_ν , the “effective number of equivalent light neutrino flavors” (Steigman, Schramm & Gunn 1977). The early expansion rate of the Universe is controlled by the total mass-energy density which, at very early epochs, is dominated by the contribution from relativistic particles. For SBBN these are photons (γ), electron-positron pairs (e^\pm), and provided they are light (i.e., relativistic), neutrinos (ν_e, ν_μ, ν_τ). For SBBN the total density, in units of the photon density, is $\rho_{\text{TOT}}^{\text{SBBN}}/\rho_\gamma = 43/8$. A convenient way to parameterize any deviation of the early expansion rate from its SBBN value is through N_ν , where

$$\rho_{\text{TOT}}/\rho_{\text{TOT}}^{\text{SBBN}} \equiv 1 + 7(N_\nu - 3)/43. \quad (1)$$

For SBBN, $N_\nu = 3$ while if $N_\nu > 3$ the early universe expands more rapidly, leaving behind more neutrons to be incorporated into ${}^4\text{He}$ during primordial nucleosynthesis; for $N_\nu \approx 3$, $\Delta Y_{\text{P}} \approx 0.01(N_\nu - 3)$. A lower bound to η , for example from D and/or D+ ${}^3\text{He}$, combined with an upper bound to Y_{P} provides an upper bound to N_ν of importance in constraining attempts to go beyond the standard model of particle physics (Steigman, Schramm & Gunn 1977; Yang et al. 1979; Steigman, Olive & Schramm 1979; Yang et al. 1984; Walker et al. 1991). The closer this upper bound is to the SBBN value of 3, the more restrictive the constraint. For example, Walker et al. (1991) found a “95% CL” constraint of $N_\nu < 3.3$, “forbidding” a fourth generation of light neutrinos or even a new light scalar particle. By 1994, Kernan & Krauss had reduced this bound to 3.04 which, if it is as claimed a “95% CL” upper bound, strongly suggests that SBBN (with $N_\nu = 3$) is not a good fit to the data. Indeed, Olive & Steigman (1995) in their reanalysis of the H II region ${}^4\text{He}$ data found a central value for N_ν of 2.2 and a 2σ (statistical) upper bound of 2.7, presaging the current crisis (Hata et al. 1995). Only when they included a possible systematic offset of $\Delta Y_{\text{sys}} = 0.005$ did Olive & Steigman (1995) recover consistency (barely) with SBBN ($N_\nu < 3.1$). Of course the problem may not (only) be with Y_{P} . Perhaps the upper bound on D (or D+ ${}^3\text{He}$) has been too severe, leading to a lower bound to η (and therefore to the SBBN predicted value of Y_{P}) which is too restrictive.

At the same time that the upper bound to Y_{P} was shrinking, tightening the noose around SBBN, the lower bound to η was in fact becoming more – not less – restrictive (Steigman & Tosi 1992, 1995; Dearborn, Steigman & Tosi 1996). For a “low” value of η the SBBN-predicted primordial abundance of D is “high”, corresponding to an SBBN-predicted primordial abundance for ${}^4\text{He}$ which is “low” (just what we “want”; see Fig. 1). But the observed ISM deuterium abundance (McCullough 1992; Linsky et al. 1993), as well as that inferred for the presolar nebula from solar system data (Geiss 1993), is “low”. A high primordial abundance can only be reconciled with a low value “here and now” if most of the gas in the present ISM (or in the presolar nebula) has been cycled through stars where D is destroyed. But there are observational consequences of an efficient cycling of gas through stars. Stars produce heavy elements and the metal abundance is observed to be small. Long-lived low-mass stars tie up gas, lowering the ratio of the mass in gas to the mass in stars which is not observed to be very small (Gould, Bahcall & Flynn 1996). Given these and similar restrictions on Galactic evolution most models of chemical evolution predict only modest D-destruction (e.g., Tosi 1996; Fields 1996 and references therein). A somewhat more direct constraint on the magnitude of possible D-destruction may be inferred from the fact that when D is destroyed it is burned to ${}^3\text{He}$ which is not entirely destroyed in stars (some of which – the low mass ones – are expected to be net producers of ${}^3\text{He}$). Again, the results of conventional chemical evolution models (e.g., Steigman & Tosi 1992; Dearborn, Steigman & Tosi 1996; Fields 1996) as well as of model-independent “inventories” (Steigman & Tosi 1995; Hata et al. 1996a) suggest little D-destruction and a relatively low primordial abundance corresponding to relatively high values of η and of Y_{P} .

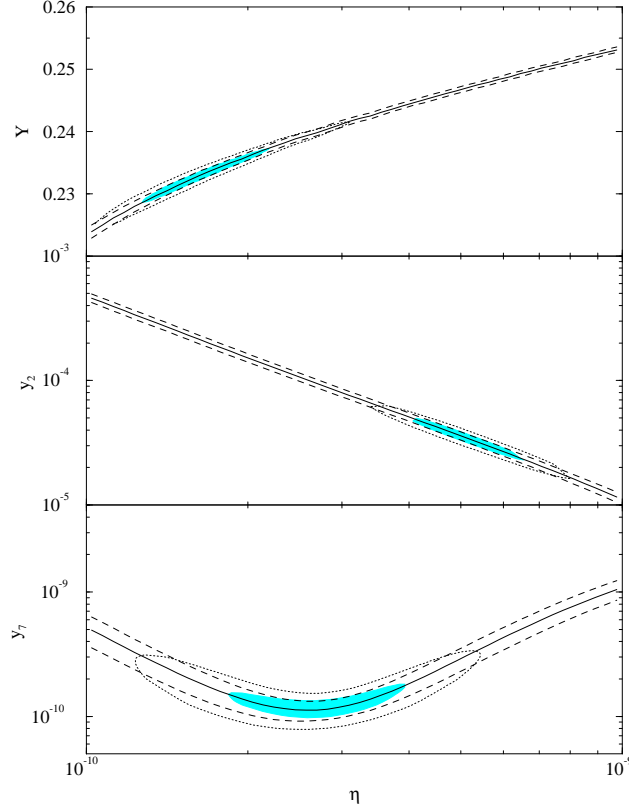


Figure 2. SBBN predictions (solid lines) for Y_P , y_{2P} and y_{7P} along with their 1σ uncertainties estimated via Monte Carlos (dashed lines). The regions constrained by observations at 68% CL (shaded) and at 95% CL (dotted lines) are also shown. (From Hata et al. 1995.)

2.1. The Crisis

This “tension” between deuterium (favoring relatively high values of η and Y_P) and helium-4 (favoring a relatively low value of η and a relatively high value of X_{2P}) constitutes the “crisis” for SBBN (Hata et al. 1995). In Figure 2 (from Hata et al. 1995) the inferred primordial abundances for D, ${}^4\text{He}$ and ${}^7\text{Li}$ are superposed on the SBBN predictions with each comparison delimiting its corresponding range of η . The challenge to SBBN posed by the data is that the ranges in η determined from D do not overlap those from ${}^4\text{He}$ (at “95% CL”); note that ${}^7\text{Li}$ is consistent with either D or ${}^4\text{He}$ while slightly preferring low η . Another way to view the problem for SBBN is to use the primordial abundances inferred from the observational data to construct the likelihood distribution for N_ν . The best fit is for $N_\nu = 2.1 \pm 0.3$ ($N_\nu < 2.6$ at “95% CL”). A measure of the “goodness of fit” of SBBN is provided by the ratio of likelihood at $N_\nu = 3$ to that at 2.1, 0.014 (Hata et al. 1995); SBBN is not a good fit to the data.

2.2. Paths To Resolution

The crisis described above may be “real” (SBBN might need to be modified) or “illusory” (one or more of the primordial abundances inferred from the observational data might be in error). If “real”, the simplest of many possibilities is that the tau neutrino is massive (Kawasaki et al. 1994). For example, if $m(\nu_\tau) \approx 10 - 20$ MeV, the tau neutrinos would not be fully relativistic at the epoch of BBN. This would modify the expansion rate, changing the number of neutrons available to be incorporated into ${}^4\text{He}$. Such a massive neutrino species would have to be unstable (to avoid “overclosing” the Universe soon after BBN) so that the deviations from the predictions of SBBN would depend on its lifetime and its decay products. Kawasaki et al. (1994) considered the simple decay channel $\nu_\tau \rightarrow \nu_\mu + \phi$, where ϕ is a light, “sterile”, scalar particle. In this case, for $10 \leq m(\nu_\tau) \leq 24$ MeV and a lifetime from ≈ 0.01 sec. to ≈ 1 sec., an appropriate reduction in Y_P may be achieved. Perhaps cosmology is pointing the way to new physics beyond the standard model of elementary particles.

If, instead, the crisis is “illusory”, many options present themselves for consideration. Since the “tension” is between D and ${}^4\text{He}$, it is natural to concentrate on each of them. Perhaps, for example, the extragalactic H II region data have led to an underestimate of the primordial helium abundance. If, rather than the inferred value of $Y_P = 0.232 \pm 0.003$ (Olive & Steigman 1995), the true value were larger by $\Delta Y \approx 0.014$, the crisis would be resolved. The small statistical uncertainty in Y_P , traceable to the large numbers of carefully observed H II regions, suggests that only an unacknowledged systematic offset in the derived ${}^4\text{He}$ abundances could account for such a large difference. Many of the potential sources of systematic error in Y would be expected to vary from source to source (e.g., ionization corrections, collisional excitation, stellar absorption, etc.) or from observer (telescope/detector) to observer (e.g., signal/noise, calibration, etc.) leading to a dispersion about the mean Y versus metallicity relation accompanying any systematic offset. The low reduced χ^2 ($\lesssim 1$) for the data compared to a simple two-parameter fit (Olive & Steigman 1995) suggests that any such offsets should be small unless all H II regions are shifted uniformly (e.g., in the unlikely case of incorrect atomic data). Thus, although it would take only a 6% upward shift in Y_P to resolve the SBBN crisis, it is difficult to identify any obvious source of such an error. Perhaps, then, deuterium is the culprit.

Certainly any attempt to use ISM and/or solar system data on D (and ${}^3\text{He}$) to infer the primordial yield is placed in peril by the necessary intervention of models of Galactic evolution. Although conventional models suggest only modest D-destruction (e.g., Tosi 1996; Fields 1996), “designer” models may permit much more astration (Scully et al. 1996). If, rather than the typical factor of 2 – 3 destruction, the ISM abundance ($X_{2\text{ISM}}$) lies below the primordial mass fraction by a factor of 5 – 10, the tension between D and ${}^4\text{He}$ would be relieved. Whether or not this is the case is better left to observations than to theory. If deuterium could be observed in very old, nearly pristine astrophysical environments, the primordial abundance could be determined without recourse to models of chemical evolution. The very high redshift ($z \approx 2 - 4$), very low metallicity ($Z \leq Z_\odot/100$) QSO absorption-line systems provide ideal targets and data from observations of such systems are now becoming available (Songaila et al. 1994; Carswell et al. 1994; Rugers & Hogan 1996; Tytler, Fan & Burles 1996;

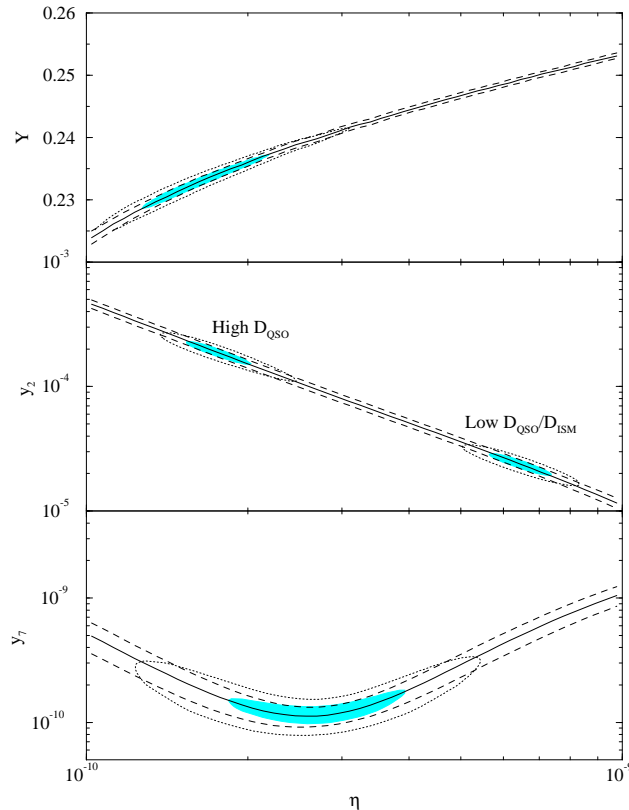


Figure 3. As for Figure 2, but with the deuterium abundances inferred from the two sets of QSO absorption data. (From Hata et al. 1996b.)

Burles & Tytler 1996). The remainder of this paper is devoted to exploring the implications for BBN (and for cosmology in general) of these new data.

3. A Tale of Two Deuterium Abundances

It is the best of times (a growing body of data on nearly primordial D from observations of high- z , low- Z QSO absorbers); it is the worst of times (the data appear inconsistent, leading to a deuterium dichotomy). On the one hand, the data of Songaila et al. (1994), Carswell et al. (1994) and Rugers & Hogan (1996) from two separate absorbing systems towards the same QSO yield a very high D abundance: $D/H = 19 \pm 4 \times 10^{-5}$, while those of Tytler, Fan & Burles (1996) and of Burles & Tytler (1996) of two systems towards two different QSOs imply a much lower value: $D/H = 2.4 \pm 0.3 \pm 0.3 \times 10^{-5}$. Although other data are available at present, they only offer bounds to the deuterium abundance and I will not consider them further here. In Figure 3, very similar to Figure 2, are shown the two deuterium determinations in comparison to the predictions of SBBN; the ^4He and ^7Li plots are exactly as in Fig. 2. This figure permits

us to explore the consequences for SBBN of the “high-D” and the “low-D” observations.

3.1. High-D

Figure 3 shows clearly that if the “high-D” abundance is primordial the tension between D and ^4He is relieved and consistency for SBBN is recovered. As Hata et al. (1996b) have found, this deuterium abundance selects (for SBBN) a “95% CL” range for η of $1.3 \leq \eta_{10} \leq 2.7$ corresponding to SBBN-predicted primordial abundances for ^4He ($0.231 \leq Y_P \leq 0.239$) and for ^7Li ($0.7 \leq 10^{10}(^7\text{Li}/\text{H}) \leq 3.0$) which are in excellent agreement with the primordial values inferred from the H II region and halo-star data respectively. Alternatively, a likelihood analysis (Hata et al. 1996b) finds for the “best value” of N_ν , 2.9 ± 0.3 , entirely consistent with SBBN ($N_\nu = 3$). Corresponding to an upper bound to Y_P of 0.243 (which includes an allowance for a possible systematic offset in Y_P of 0.005; Olive & Steigman 1995), “high-D” sets an upper bound to N_ν of 3.6, forbidding the existence of a fourth generation of light neutrinos (or, its equivalent) but permitting (just barely) a light scalar.

There are two problems associated with such a high value for the primordial abundance of deuterium. Although perfectly consistent with SBBN, this high initial D abundance requires that 90% or more of the present ISM has been cycled through stars (i.e., $X_{2P}/X_{2\text{ISM}} = 13 \pm 3$). Can such efficient stellar processing occur without overproducing the present metallicity and/or using up the interstellar gas? Conventional evolution models suggest no. It will be a challenge to “designer” models to see if this is possible (consistent with observations). Another challenge posed by the identification of “high-D” with the primordial abundance of deuterium is the correspondingly low baryon density it implies. In terms of the density parameter Ω_B (the ratio of the present mass density in baryons to the “critical” density) and the normalized Hubble parameter h ($H_0 = 100h$ km/sec/Mpc),

$$\Omega_B h^2 = 3.66 \times 10^{-3} \eta_{10}, \quad (2)$$

so that for $1.3 \leq \eta_{10} \leq 2.7$, $0.005 \leq \Omega_B h^2 \leq 0.010$. This corresponds to a very low baryon density; for H_0 between 50 and 100 km/sec/Mpc, $0.005 \leq \Omega_B \leq 0.040$. As we shall see shortly, this low baryon density may be in conflict with observations of the x ray-emitting hot gas in rich clusters of galaxies (White et al. 1993; Steigman & Felten 1995; Hata et al. 1996b; Steigman, Felten & Hata 1996). Before turning to considerations of mass density, let us first consider the implications for SBBN of the “low-D” abundance.

3.2. Low-D

If, indeed, the “low-D” determinations reflect the primordial D abundance, SBBN is in trouble. In this case the situation is somewhat worse than before (the tension between D and ^4He is increased) due to the rather low value for X_{2P} implied by the “low-D” QSO data. This abundance, which leaves very little room for any D-destruction ($X_{2P}/X_{2\odot} = 1.0 \pm 0.4$; $X_{2P}/X_{2\text{ISM}} = 1.6 \pm 0.4$), identifies a high range for η ($5.1 \leq \eta_{10} \leq 8.2$) corresponding to high predicted (for SBBN) primordial abundances of ^4He ($0.246 \leq Y_P \leq 0.252$) and of ^7Li ($3.0 \leq 10^{10}(^7\text{Li}/\text{H}) \leq 7.8$). Now consistency with SBBN requires not only that the

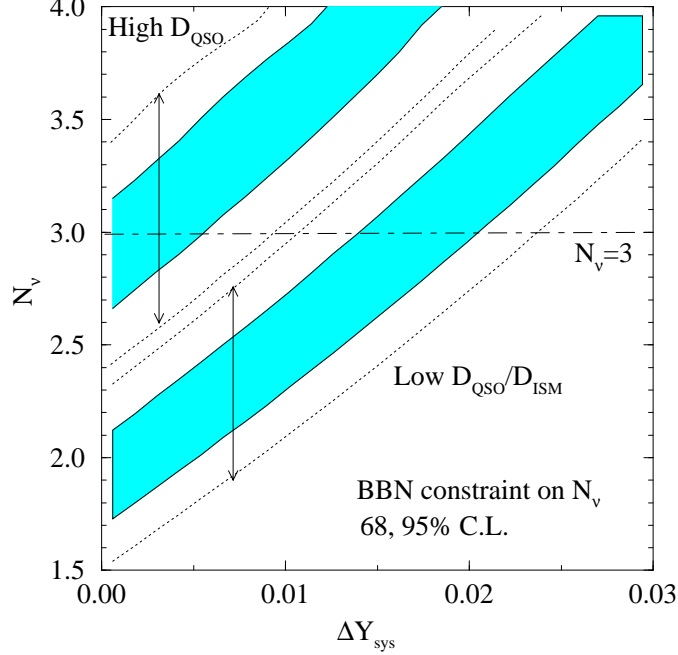


Figure 4. The allowed range of N_ν at 68% CL (shaded) and 95% CL (dotted lines) for “high-D” and for “low-D” as a function of the systematic offset (ΔY_{sys}) in the value of Y_{P} derived from H II region data. (From Hata et al. 1996b.)

H II region observations have systematically underestimated Y by an amount of order 0.017 (7%), but also that the “Spite plateau” halo stars should have destroyed or diluted their initial lithium by more than a factor of three. In contrast to these apparently serious problems, the baryon density corresponding to “low-D” is quite reasonable, $0.019 \leq \Omega_{\text{B}} h^2 \leq 0.030$ (for $1/2 \leq h \leq 1$, $0.12 \geq \Omega_{\text{B}} \geq 0.019$).

3.3. N_ν Revisited

If the QSO D-abundances are used to constrain η and N_ν is allowed to be a free parameter, the BBN-predicted abundance of ${}^4\text{He}$ will depend on N_ν . We have seen that for “high-D” and for $\Delta Y_{\text{sys}} = 0$, SBBN ($N_\nu = 3$) is a good fit. However, as ΔY_{sys} is increased with η fixed by “high-D”, the “best-fit” value of N_ν also increases. Eventually, for sufficiently large ΔY_{sys} , $N_\nu = 3$ is no longer a good fit and SBBN is in trouble. This behavior is shown in Figure 4 from Hata et al. (1996b). For $\Delta Y_{\text{sys}} > 0.01$, $N_\nu > 3.0$ at “95% CL” and SBBN is no longer consistent with the data; a new D/ ${}^4\text{He}$ “tension” appears. In contrast, in the absence of any systematic offset in Y_{P} , the η range identified by “low-D” is not consistent with SBBN (see Fig. 4). However, as ΔY_{sys} is increased beyond 0.01,

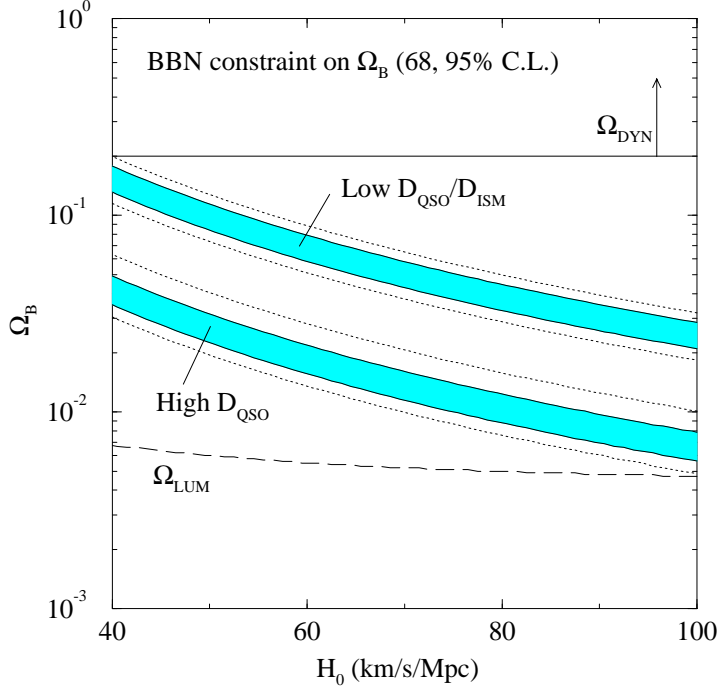


Figure 5. The baryon density parameter (Ω_B) as a function of the Hubble parameter (H_0) for the 68% CL (shaded) and the 95% CL (dotted) ranges corresponding to “high-D” and “low-D”. The upper bound on the density of “luminous” matter is shown by the dashed line and the solid line represents the lower bound to the total mass density. See the text for details and references. (From Hata et al. 1996b.)

a good fit to SBBN may be achieved. Thus, with increasing ΔY_{sys} consistency for SBBN shifts from “high-D” to “low-D”.

3.4. Primordial D and the Baryon Density

The conundrum posed by the contradictory results for primordial deuterium derived from the embryonic studies of QSO absorption-line systems should be resolved as more observational data are accumulated. Until then we may search for clues elsewhere. Consistency for SBBN requires not only that the predicted primordial abundances agree with those inferred from observations, but also that the corresponding range of nucleon density identified by BBN agree with other astrophysical/cosmological data. In Figure 5 (Hata et al. 1996b) are shown the ranges in Ω_B as a function of the Hubble parameter H_0 corresponding to “low-D” and to “high-D”. Also shown is a lower bound to the baryon density inferred from observations of the amount and distribution of “luminous” matter (Ω_{LUM}) in the Universe (Salucci & Persic 1996) along with a lower bound to the total mass-energy density (Ω_{DYN}) derived from the dynamics of groups and clusters of galaxies and from large-scale flows (Ostriker & Steinhardt 1995). Both “low-D” and “high-D” η ranges are consistent with these bounds and both

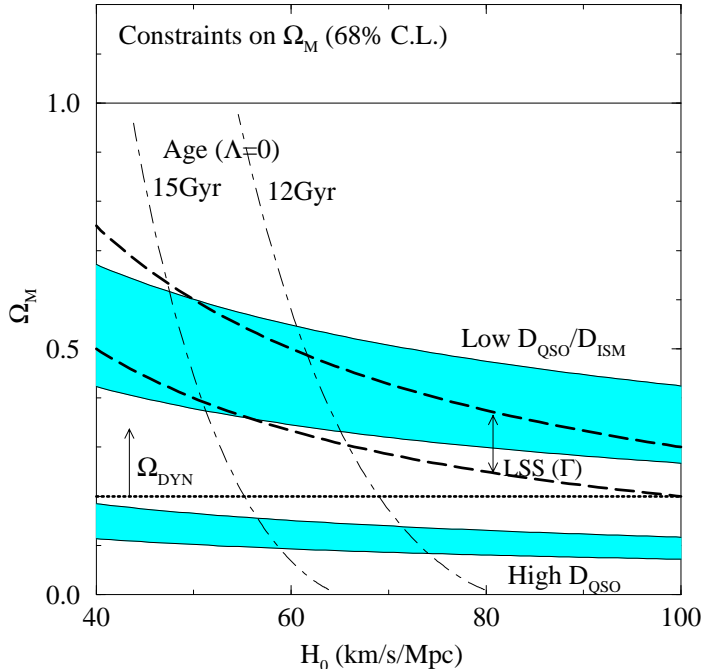


Figure 6. Upper bounds on the total mass density parameter (Ω_M) as a function of the Hubble parameter (H_0) for “high-D” and “low-D” (shaded bands at 68% CL) along with constraints from the “shape parameter” ($\Gamma = \Omega_M h$) and from dynamics (Ω_{DYN}). This figure is for a zero cosmological constant ($\Lambda = 0$). Also shown are the loci of Ω_M vs. H_0 for two choices of the present age of the Universe. (From Hata et al. 1996b.)

leave room for non-baryonic dark matter ($\Omega_B < \Omega_{\text{DYN}}$) and for dark baryons ($\Omega_B > \Omega_{\text{LUM}}$). However, the low values of Ω_B implied by the “high-D” data do provide a hint of a problem. Is such a low baryon density really consistent with all the observational data?

3.5. X-Ray Clusters and the Baryon Density

Rich clusters of galaxies are expected to provide a “fair” sample of the universal baryon fraction ($f_B \equiv \Omega_B/\Omega_M$); see, e.g., White & Frenk (1991); White et al. (1993); White & Fabian (1995); Evrard et al. (1995). If, indeed, f_B is equal to the ratio of the cluster baryonic mass (M_B) to the total gravitating mass (M_{TOT}), x-ray observations of rich clusters may be used to infer Ω_M from f_B and Ω_B (or η). The x-ray flux provides information on the amount of hot gas (baryons) M_{HG} while the spectrum (x-ray temperature) is a probe of the depth of the potential well (under the assumption of hydrostatic equilibrium) and, hence, of M_{TOT} . Since some cluster baryons are in the luminous galaxies and there may be dark baryons in cluster MACHOS (Gould 1995), $f_B > f_{\text{HG}} = M_{\text{HG}}/M_{\text{TOT}}$, resulting in the bound $\Omega_M < \Omega_B/f_{\text{HG}}$. From the analysis of Evrard et al. (1995)

and from Evrard (1995, Private Communication), $f_{\text{HG}} = (0.07 \pm 0.01)h^{-3/2}$, so that

$$\Omega_{\text{M}}h^{1/2} < (0.052 \pm 0.008)\eta_{10}. \quad (3)$$

In Figure 6 (Hata et al. 1996b) this upper bound on Ω_{M} is plotted versus H_0 for the η ranges singled out by the QSO “low-D” and “high-D” determinations. Also shown in Figure 6 is the “dynamical” lower bound from Figure 5 along with the large scale structure constraint from the “shape parameter” $\Gamma = \Omega_{\text{M}}h = 0.25 \pm 0.05$ (Peacock & Dodds 1994). For a cosmology without a cosmological constant ($\Lambda = 0$) the loci of Ω_{M} versus H_0 for two choices of the present age of the Universe are shown as well. The conclusion to be drawn from Figure 6 is that these cosmological constraints favor the “high- η ” range consistent with “low-D” and avoid the range corresponding to “high-D”. A similar result obtains for “flat” cosmologies with a cosmological constant ($\Omega_{\text{M}} + \Omega_{\Lambda} = 1$) or for mixed, “hot-plus-cold” dark matter ($\Omega_{\text{B}} + \Omega_{\text{CDM}} + \Omega_{\text{HDM}} = 1$) models (Hata et al. 1996b). The x-ray cluster, large-scale structure and dynamical data prefer “high- η , low-D”.

4. Summary

Over the years primordial nucleosynthesis has provided spectacular support for the standard hot big bang cosmology. For a nucleon abundance consistent with present density determinations, the SBBN-predicted abundances of D, ^3He , ^4He and ^7Li , which span some nine orders of magnitude, agree qualitatively with the primordial abundances inferred from observational data. This success has inspired careful quantitative analyses which serve as a probe of consistency and of new physics beyond the standard models of particle physics and cosmology. These recent investigations have uncovered some potential problems. In particular, the primordial abundances of deuterium and of helium-4 inferred from observations of the ISM and the solar system (for D) and of extragalactic H II regions (for ^4He) appear to be inconsistent with the predictions of SBBN. Either the derived values of $X_{2\text{P}}$ or of Y_{P} (or both) are wrong or SBBN should be modified. The sense of the discrepancy is that the primordial abundances of D and/or ^4He should have been underestimated, or the early universe should have expanded more slowly. The latter possibility could be achieved if the tau neutrino were very massive (10 – 20 MeV) and unstable (0.01 – 1 sec); this option can be (is being) tested at current accelerators. The large body of accurate observations of ^4He in low metallicity H II regions suggests it is unlikely that Y_{P} has been underestimated due to a statistical fluctuation and the small dispersion of the data suggests that many of the potential sources of systematic error may be negligible. Nevertheless, it is difficult to entirely exclude a systematic offset of unknown origin. In contrast, until recently the deuterium observations have been restricted to “here and now” requiring the adoption of some assumptions/constraints on chemical evolution to derive the primordial abundance. Thus, deuterium emerges as a possible weak link in the chain of tests of the consistency of SBBN. In the best of all worlds D might be observed “there and then” avoiding the uncertain chemical evolution corrections. Great hopes have been raised by claimed observations of deuterium in a few, high red-

shift, low metallicity QSO absorption line systems. Unfortunately, this field is in its infancy and the abundances derived from current data appear inconsistent. These data have led to a deuterium dichotomy, identifying not one but two, mutually exclusive (if the claimed statistical uncertainties are correct), primordial abundances for D. “High-D”, corresponding to a low range for η , is entirely consistent with the predictions of SBBN and the inferred primordial abundances of the other light nuclides. Nonetheless, this choice requires that the Galaxy has been very (too?) efficient in cycling gas through stars to reduce the primordial abundance of D to its observed value “here and now”. Also, the low baryon density implied by “high-D” and SBBN may be problematic. In contrast, “low-D” exacerbates the already threatening crisis for SBBN, favoring a high range for η corresponding to SBBN yields of ^4He and ^7Li which appear to exceed the primordial abundances derived from the observational data. This higher range for η may also be preferred by other observational data of x-ray clusters and large-scale structure. As the approach to primordial deuterium via high-z, low-Z QSO absorbers grows from infancy to maturity, it is hoped that these contradictions will be resolved. Whether the answer will be “high-D”, “low-D”, or something else is anyone’s guess.

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